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The decomposition of energy-related carbon emission and its decoupling with economic growth in China

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A B S T R A C T

In order to find the efficient ways to reduce carbon emission intensity in China, we utilize the LMDI method to decompose the changes of China's carbon emissions and carbon emission intensity from 1996 to 2010, from the perspectives of energy sources and industrial structure respectively. Then we introduce the decoupling index to analyze the decoupling relationship between carbon emissions and economic growth in China. The results indicate that, on the one hand, economic growth appeared as the main driver of carbon emissions increase in the past decades, while the decrease of energy intensity and the cleaning of final energy consumption structure played significant roles in curbing carbon emissions; meanwhile, the secondary industry proved the principal source of carbon emissions reduction among the three industries and had relatively higher potential. On the other hand, when the decoupling relationship is considered, most years during the study period saw the *relative decoupling effect* between carbon emissions and economic growth, which indicated that the reduction effect of inhibiting factors of carbon emissions was less than the driving effect of economic growth, and the economy grew with increased carbon emissions; there appeared the *absolute decoupling effect* in 1997, 2000 and 2001, which implied that the economy grew while carbon emissions decreased; whereas *no decoupling effect* was identified in 2003 and 2004.

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1. Introduction

In recent years, the international community has paid enormous attention to addressing the climate change issues which are mainly caused by the emission of greenhouse gases (GHG) [1]. Based on the carbon emitting speed now, it is predicted that the global temperature will increase on average 1.3 °C compared to the level during the pre-industrial revolution period [2]. In view of the immense pressure to slow down global warming, more and more countries have joined into the carbon reduction procession. Since the reform and opening up in late 1970s, China's economy has experienced sustained take-off, which has made China the second largest economy in the world but also driven China's carbon emissions to lead the world. China has surpassed the US and became the largest CO_2 emitter in the world wide since 2008, and in 2012, China's CO_2 emission reached 9.21 billion tons, which accounted for 26.7% of the total emissions around the world [3].

It should be noted that as a responsible country, China has made tremendous efforts to reduce carbon emission intensity (carbon emissions per unit of gross domestic product (GDP)); specifically, China's carbon emission intensity dropped from 3.59 kg/US dollar in 2005 prices in 1990 to 1.79 in 2010 [4] with a 71% decrease in total and a 3.8% annual decrease rate on average; during the same time period, China's energy intensity dropped 58% with an annual decline rate of 4.2%. Meanwhile, before the Copenhagen climate change conference in 2009, China promised a target to reduce carbon emission intensity by 40–45% by 2020 compared with the level in 2005. During the 12th Five-Year Plan period (2011–2015), China also proposed a quantitative target to drop carbon emission intensity by 17%.

In order to achieve these ambitious targets in the wake of steady economic growth, it proves urgent for China to find the effective and efficient ways to control carbon emissions, coordinate the relationship between carbon emissions and economic growth, and ensure a continual decline in carbon emission intensity. This is the major motivation of this paper. On the other hand, the paper appears as a good supplement for the CO_2 emissions decomposition analysis in China, not only the research contents but also the research methods, which is another motivation here. Therefore, in this paper, we decompose the changes of energy-related CO_2 emissions and carbon emission intensity in China during 1996–2010, which is in line with China's 9th, 10th and 11th Five-Year Plan periods. In the meantime, based on the decomposition results, we introduce the decoupling index to analyze the decoupling relationship between China's carbon emissions and economic growth. And then some policy recommendations are provided to support the decision-making of China's government to achieve carbon intensity targets.

As for the contribution in this paper, three aspects can be obtained. First, in view of decomposition object, except for the decomposition of CO_2 emissions changes, this paper also decomposes the changes of carbon emissions intensity during 1996–2010. Second, in view of the methodology, this paper extends the common LMDI decomposition analysis in CO_2 emissions changes, through examining the effect of final energy consumption structure on CO_2 emissions changes from the perspectives of energy sources and industrial structure simultaneously. Third, based on the decomposition results of CO_2 emissions changes, we introduce the decoupling index to investigate the decoupling relationship between CO_2 emissions and economic growth in China on the national level; and we also explore the affecting factors of the decoupling relationship.

The rest of the paper is organized as follows. Section 2 gives the related literature review. Section 3 presents the research methodologies and data definitions. Section 4 discusses the empirical results and puts forward some policy recommendations, while Section 5 concludes the paper.

2. Related literature review

It has been confirmed that CO_2, as the main type of greenhouse gases (GHG), contributes about 60% of total greenhouse effect in the world [5,6]. As a result, climate change issues have received more and more attention by academics, practitioners and politicians since 1980s especially in the recent decade. In particular, an increasing number of studies start to decompose the changes of CO_2 emissions to explore their driving factors.

As for the approaches of CO_2 emissions decomposition, there are primarily three categories, i.e., the structural decomposition analysis (SDA), the index decomposition analysis (IDA) and the production-theoretical decomposition analysis (PDA). The SDA approach is based on the input–output model in quantitative economics to decompose carbon emission changes by using the input–output tables in specific years. Chang and Lin [7] employed structural decomposition analysis to examine emission trends and effects for industrial CO_2 emission changes in Taiwan during 1981–1991. Results indicate that the level of domestic final demand and exports is the primary factor for the increase of CO_2 emission. On the other hand, the effect of decreasing industrial CO_2 intensity is a main reducing factor. Chang et al. [8] used the structural decomposition method to identify the major factors and industries contributing to the CO_2 emission changes in Taiwan during 1984–2004. The results show that the highway, petrochemical materials, steel and iron are primary industries affecting CO_2 emissions in Taiwan. The level of exports and the level of domestic final demand are the largest contributors to the carbon emission increment. The major decreasing effect comes from industrial energy coefficient and the structure of domestic final demand. Tian et al. [9] conducted structural decomposition analysis to quantify the contribution of technological and socio-economic factors to the CO_2 growth in Beijing from 1995 to 2007. The results indicate that final demand level and production structure change led to carbonizing Beijing significantly, while energy intensity improvement is Beijing's sole prominent source on decarbonizing its economic development. In order to uncover driving forces for provincial CO_2 emission in China, Geng et al. [10] undertook a case study on the CO_2 emission growth in Liaoning province of China during 1997–2007 by using the structural decomposition analysis. Research outcomes indicate that rapid increase of per capita consumption activities is the main driver for emission increment, while energy intensity and energy structure partly offset the CO_2 emission increase. Nevertheless, because of the dependence on the input–output tables, the decomposition can only be performed additively, which constrains the extensive use of SDA in empirical analyses [11].

Compared to the SDA approach, the application of IDA proves more widely, which mainly contains the Laspeyres and Divisia index approaches. The Laspeyres index approach is easier to understand without the "zero-value" problem, but the decomposition results have large residual terms. Based on the traditional Laspeyres index, Sun [12] proposed "the complete decomposition model" also called the refinement of Laspeyres index, which can settle the residual problem very well, but its decomposition formulae appears very complicated when the number of impact factors exceeds three [11]. Paul and Bhattacharya [13] adopted "the complete decomposition model" to investigate the factors influencing the energy-related CO_2 emissions changes in India during the period 1980–1996. The results show that economic growth has the largest positive effect in CO_2 emissions changes in all the major economic sectors. Emissions of CO_2 in industrial and transport sectors show a decreasing trend due to improved energy efficiency and fuel switching. By using the refined Laspeyres method, Kumbaroğlu [14] carried out a decomposition analysis on CO_2 emission changes in Turkish over 1990–2007 at sectoral level

based on disaggregated data. As a result, it is found that the scale effect (production activity) is a major source of emission increase in the electricity, manufacturing and transport sectors. Manufacturing and transport sectors emissions decrease mainly due to energy intensity improvement, while compositional changes prove effective in reducing emissions in the electricity sector.

Moreover, the Divisia index mainly includes the arithmetic mean Divisia index (AMDI) and log mean Divisia index (LMDI), which use the arithmetic mean weight function and log mean weight function respectively. It should be noted that the AMDI not only contains residual problem but also cannot solve the "zero-value" problem in the data. Then Ang and Choi [15] put forward a refined Divisia index method using logarithmic mean weight functions in 1997, which could well settle the residual and "zero-value" problems and satisfy other conditions of "perfect decomposition approaches" simultaneously. We consider this method as the early decomposition form of LMDI. Then Ang et al. [16] extended the above approach which was based on decomposition of an aggregate index, and proposed another refined Divisa index method based on logarithmic mean weight functions and decomposition of a different quantity in 1998. The appellation of LMDI I and LMDI II first appeared in 2001, when Ang and Liu [17] presented a new energy decomposition method, called the Log-Mean Divisia Index Method I (LMDI I). The method has the desirable properties of perfect decomposition and is consistent in aggregation. Ang and Liu [17] also pointed out that the early LMDI decomposition form proposed by Ang and Choi [15] in 1997 was not consistent in aggregation. They referred the early one in 1997 as the Log-Mean Divisia Index Method II (LMDI II) for easy reference. In 2003, Ang et al. [18] further indicated that the LMDI I was closely related to the LMDI II, and the method proposed by Ang et al. [16] in 1998 was the additive form of LMDI I, while method by Ang and Liu [17] in 2001 was the multiplicative form. Therefore, we can figure out that the LMDI II was proposed in 1997 and the LMDI I was proposed in 2001 (as the appellation first appeared in 2001). In fact, the LMDI I method has become one of the most extensively used methods in the decomposition of CO_2 emission changes, as meeting all those constraints. Tunc et al. [5] tried to identify the factors that contribute to changes in CO_2 emissions for the Turkish economy by utilizing the LMDI method. Their analysis shows that economic activity is the main component determining the CO_2 emissions changes, while intensity effect is another significant influencing factor. Focusing on Turkish manufacturing industry, Akbostanci et al. [19] used the LMDI method to decompose the changes in the CO_2 emissions into five components. It is also found that changes in total industrial activity and energy intensity are the primary factors determining CO_2 emissions changes in Turkish manufacturing industry during the study period. Jeong and Kim [20] decomposed Korean industrial manufacturing CO_2 emissions changes during 1991–2009 using the LMDI method, both multiplicatively and additively. The results indicate that the structure effect (industrial activity mix) and intensity effect (sectoral energy intensity) play significant roles in reducing CO_2 emissions, and the structure effect plays a bigger role than the intensity effect. Malla [21] used the LMDI method to examine the three defined factors affecting the evolution of CO_2 emissions from electricity generation in seven countries, which are electricity production, electricity generation structure and energy intensity of electricity generation. The findings indicated that production effect was the major factor responsible for the rise in CO_2 emissions during the period 1990–2005. The generation structure effect also contributed to CO_2 emissions increase, while the energy intensity effect was responsible for the modest reduction in CO_2 emissions during this period. Employing the LMDI method, Mahony et al. [22] analyzed the driving forces of CO_2 emissions in eleven final energy consuming sectors in Ireland. The results illustrate that scale effects predominate in acting to increase emissions in the economic and transport sectors, while improvements in energy intensity are notable in the economic sectors and in the residential sector.

In addition to the SDA and IDA approaches, with the increasing application of production theory, distance functions and data envelopment analysis (DEA) technique in energy and environmental research area, the production-theoretical decomposition analysis (PDA) approach is gradually developed. Zhou and Ang [23] presented an alternative approach to decompose the change of aggregate CO_2 emissions over time using two Shephard input distance functions and the environmental data envelopment analysis technology in production theory into contributors from seven factors, and firstly call this method as the PDA approach, to the best of our knowledge. Besides defining two input distance functions for input and undesirable output, Zhang et al. [24] extended Zhou and Ang [23] to decompose the CO_2 emissions changes of 20 developing countries into the contributors from nine factors by defining the Shephard output distance function for the desirable output. Empirical results indicate that the economic (GDP) growth is the most important contributor to CO_2 emissions increase, while good output technical change is the most important component for CO_2 emissions reduction. Zhang and Da [25] employed the PDA approach combined with environmental DEA technique and distance functions to decompose China's CO_2 emissions changes at the provincial and regional levels during the 11th Five-Year Plan period. The results show that economic growth and energy consumption are the two main drivers of CO_2 emissions increase during the study period, while the improvement of carbon abatement technology and the reduction in energy intensity play significant roles in curing CO_2 emissions. Overall, compared to the other two decomposition approaches, the most significant advantage of PDA is that it can reveal the effect of carbon emission factors related with production technology and efficiency; and it also has the drawback that it cannot reflect the effect of structure components (such as industrial structure, energy consumption structure) as SDA and IDA do [23].

As one of the biggest carbon emitters around the world, China's carbon emissions have received more and more attention, and an increasing number of studies use the LMDI approach to decompose China's carbon emission changes (see Table 1). For instance, Wang et al. [26] attributed the changes of aggregated CO_2 in China during 1957–2000 to carbon emission coefficient, energy consumption structure, energy intensity, GDP per capita and population level based on the LMDI approach, and indicated that the improved energy intensity proves the main factor curbing carbon emissions. In addition, fuel switching and renewable energy penetration also exert positive effects on CO_2 decrease. Liu et al. [27] utilized the LMDI approach to decompose carbon emission changes of Chinese industrial sectors during 1998–2005 into carbon emission coefficient of heat and electricity, energy intensity, industrial structural shift, industrial activity and final fuel shift, and argue that the industrial activity and energy intensity are the overwhelming contributors to carbon emission changes. Lin and Moubarak [28] examined the influencing factors of energy-related carbon emissions in Chinese textile industry during 1986–2010. By separating the study interval into five subintervals, they contrast the variation of carbon emission impact factors in each subinterval and find that textile industrial activity is the major factor that contributes to the increase of CO_2 emissions while energy intensity has volatile reduction effect along the study period. Zhang et al. [29] analyzed the carbon emission changes of electricity generation in China during 1991–2009, and the main results imply that coal product is the main fuel type for thermal power generation, which accounts for more than 90% of CO_2 emissions from electricity generation, and economic activity

Table 1
Representative literature for decomposition of CO_2 emissions changes in China.

Authors	Research object	Time interval	Research conclusions
Wang et al.	The changes of China's aggregated CO_2	1957–2000	Improved energy intensity, fuel switching and renewable energy penetration are the main factors curbing carbon emissions.
Liu et al.	Carbon emission changes of Chinese industrial sectors	1998–2005	The industrial activity and energy intensity are the overwhelming contributors to carbon emission changes.
Lin and Moubarak	Energy-related carbon emissions in Chinese textile industry	1986–2010	Industrial activity is the major factor that contributes to the increase of CO_2 emissions while energy intensity has volatile reduction effect.
Zhang et al.	The carbon emission changes of electricity generation In China	1991–2009	Economic activity is the most important contributor to the increase of carbon emissions, while the improvement of electricity generation efficiency plays the dominant role in decreasing CO_2 emissions.
Wang et al.	Energy-related CO_2 emissions in Jiangsu province	1995–2009	Economic activity is the critical factor of carbon emissions growth and energy intensity effect plays the dominant role in the decreasing way.

Table 2
Representative literature for decomposition of carbon emissions intensity in China.

Authors	Research object	Time interval	Research conclusions
Zhang et al.	Carbon emission intensity changes	1991–2006	The decline of energy intensity is the main promoting factor to carbon emission intensity reduction, while the effect of carbon emission coefficient and industrial structure proves weaker.
Fan et al.	Primary energy-related carbon intensity and the material production sectors' final energy-related carbon intensity	1980–2003	The reduction in real energy intensity is the overwhelming contributor to the decline of carbon emission intensity.
Tan et al.	Carbon emissions intensity changes	1998–2008	The electric power industry contributes 59.59% of carbon emission intensity, which mainly benefits from the decrease of energy intensity in power generation.

is the most important contributor to the increase of carbon emissions, while the improvement of electricity generation efficiency plays the dominant role in decreasing CO_2 emissions. Wang et al. [30] used the LMDI approach to investigate the driving forces of energy-related CO_2 emissions in Jiangsu province during the period 1995–2009 and hold that economic activity is the critical factor of carbon emissions growth and the energy intensity effect plays the dominant role in the decreasing way.

Meanwhile, there also appears a body of literature considering the decomposition of carbon emission intensity changes in China (see Table 2). For instance, Zhang et al. [31] applied "the complete decomposition model" proposed by Sun [12] to decompose China's carbon emission intensity changes during 1991–2006 into energy intensity, carbon emission coefficient and industrial structure. The results indicate that the decline of energy intensity is the main promoting factor to carbon emission intensity reduction, while the effect of carbon emission coefficient and industrial structure proves weaker. Based on the Adaptive Weighting Divisia (AWD) method, Fan et al. [32] quantitatively investigated the driving forces of China's primary energy-related carbon intensity and measured the material production sectors' final energy-related carbon intensity during 1980–2003, and found that the overwhelming contributor to the decline of carbon emission intensity is the reduction in real energy intensity. Tan et al. [33] examined the forces to reduce China's CO_2 emission intensity between 1998 and 2008 using the LMDI approach and pointed out that the electric power industry contributes 59.59% of carbon emission intensity reduction, which mainly benefits from the decrease of energy intensity in power generation.

In addition, the rapid growth of CO_2 emissions in emerging giant countries raises public attention to sustainable economic development for those countries including China. In fact, in recent years, a growing number of studies have been focused on the decoupling relationship between carbon emissions or environmental pressure and economic growth across the world (see Table 3). For example, Zhang [34] introduced the decoupling index into resource and environmental field in 2000 [35] and OECD regards the decoupling effect as disconnecting the relationship between economic growth and environmental pressure and divides it into the absolute and relative decoupling effect [36]. Freitas and Kaneko [35] utilized the decoupling analysis method proposed by OECD to investigate the decoupling relationship between economic growth and CO_2 emissions in Brazil during the period 2004–2009 and found that there existed absolute decoupling effect in 2009. Also based on the OECD method, Lu et al. [37] examined the decoupling effects among economic growth, transport energy demand and CO_2 emissions in Germany, Japan, Korea and Taiwan and found that the growth of economy and vehicle ownership are the most important factors for the increased CO_2 emissions. In order to investigate the degree of decoupling effect in EU, Tapio [38] introduced the elasticity theory into the decoupling index and created the Tapio decoupling analysis theoretical framework. Diakoulaki and Mandaraka [39] focused on the CO_2 emission changes in the EU manufacturing sectors during 1990–2003 and combined "the complete decomposition model" proposed by Sun [12] with the decoupling index not only to discover the influencing factors of CO_2 emission changes but also evaluated the contribution made by these factors on the decoupling between CO_2 emissions and industrial growth. And Wang et al. [30] combined the LMDI decomposition approach with the decoupling index to examine the decoupling effect between carbon emissions and economic growth in Jiangsu province during 1995–2009, and found that carbon emissions and economic growth demonstrated the absolute decoupling effect in 1997 and 2001, no decoupling effect during 2003–2005 while relative decoupling effect in the rest periods. Moreover, the decrease of energy intensity and the cleaning of energy consumption structure are the main contributors to the decoupling effect between carbon emissions and economic growth in Jiangsu province. These previous studies provide helpful references for the decoupling analyses in this paper.

Based on the previous studies, we may decompose the changes of final energy-related CO_2 emissions and carbon emission intensity in China from 1996 to 2010 (the 9th, 10th and 11th Five-Year

Table 3
Representative literature for environmental decoupling analyses.

Authors	Research object	Time interval	Research conclusions
Freitas and Kaneko	The decoupling relationship between economic growth and CO_2 emissions in Brazil	2004–2009	The decoupling effect was highlighted when economic activity and CO_2 emissions moved in opposite directions in 2009.
Lu et al.	The decoupling effects among economic growth, transport energy demand and CO_2 emissions in four regions	1990–2002	Energy conservation performance and CO_2 mitigation in each country are strongly correlated with environmental pressure and economic driving force, except for Germany in 1993 and Taiwan during 1992–1996.
Diakoulaki and Mandaraka	Evaluating the progress made in EU countries in decoupling emissions from industrial growth	1990–2003	Most EU countries make a considerable but not always sufficient decoupling effort, while no significant acceleration is observed in the post-Kyoto period.
Wang et al.	The decoupling effect between carbon emissions and economic growth in Jiangsu province	1995–2009	Carbon emissions and economic growth demonstrated the absolute decoupling effect in 1997 and 2001, no decoupling effect during 2003–2005 while relative decoupling effect in the rest periods.

Plan periods) by using the LMDI approach. This period owns the highest economic growth rates, so the empirical results will be good references for China's government to formulate scientific and realistic carbon reduction policies under the on-going development pattern. Moreover, except for the decomposition of CO_2 emissions changes, this paper also decomposes the changes of carbon emissions intensity during this period. To the best of our knowledge, the research on the decomposition of carbon emissions intensity changes in China, no matter using the LMDI method or other decomposition approaches, appears not enough. Under this circumstance, we employ the LMDI method to decompose carbon emissions intensity changes in China into energy intensity, industrial structure and energy consumption structure. Moreover, as the extension of common decomposition, we may examine the effect of final energy consumption structure on CO_2 emission changes from the perspectives of energy sources and industrial structure. Then, based on the decomposition results, we may investigate the decoupling relationship between CO_2 emissions and economic growth on the national level in China through the combination of LMDI approach with decoupling index. In brief, currently, there is little literature discussing the decoupling effect between China's carbon emissions and economic growth on the national level through the combination of decomposition approaches with decoupling index. We also test the effect of energy intensity, industrial structure and energy consumption structure on the decoupling progress.

3. Methodologies and data definitions

3.1. Energy-related CO_2 emissions estimation approach

We apply the approach proposed by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [40] to estimate CO_2 emissions related to the final consumption of coal, oil and natural gas in energy balance tables, as shown in the following equation:

$$C^t = \sum_{i,j} C_{ij}^t = \sum_{i,j} E_{ij}^t \times F_j \times \frac{44}{12} \tag{1}$$

where C^t denotes the total CO_2 emissions in year t and is quoted in ten thousand tons; C_{ij}^t means the CO_2 emissions related to energy source j consumed by industry i in year t, while $i = 1, 2, 3$ denotes the primary, secondary and tertiary industries respectively; and $j = 1, 2, 3$ indicates coal, oil and natural gas respectively; E_{ij}^t means the use of energy source j of industry i in year t; while F_j denotes the carbon emission coefficient of energy source j, which is proposed by China Sustainable Energy and Carbon Emissions Scenario Analysis Comprehensive Report released by Energy Research Institute, National Development and Reform Commission of China [41]. Specifically, the carbon emission coefficients of coal, oil and natural gas are 0.7476, 0.5825 and 0.4435 respectively. And 44/12 indicates the conversion coefficient from carbon to carbon dioxide.

3.2. CO_2 emission change decomposition approach

In order to decompose the energy-related CO_2 emissions, we rewrite Eq. (1) as follows:

$$C^t = \sum_{i,j} C_{ij}^t = \sum_{i,j} \frac{E_{ij}^t}{E_i^t} \times \frac{E_i^t}{Y_i^t} \times \frac{Y_i^t}{Y^t} \times Y^t \times F_j \times \frac{44}{12} \tag{2}$$

where E_i^t means the total final energy consumption of industry i in year t; Y_i^t denotes the added value of industry i in year t; and Y^t indicates the GDP in year t. We define $CS_i^t = (E_{ij}^t)/(E_i^t)$, which indicates the final energy consumption structure of industry i and similarly appears in Hammond and Norman [42] and Jeong and Kim [20]; $EI_i^t = (E_i^t)/(Y_i^t)$, which means the energy intensity of industry i; and $IS_i^t = (Y_i^t)/(Y^t)$, which implies the industrial structure in year t. Therefore, Eq. (2) can be expressed as follows:

$$C^t = \sum_{i,j} CS_i^t \times EI_i^t \times IS_i^t \times Y^t \times F_j \times \frac{44}{12} \tag{3}$$

It should be noted that the final energy consumption structure CS_i^t in Eq. (3) is based on the perspective of the three industries (i.e., the primary, secondary and tertiary industries). Moreover, we can also obtain the final energy consumption structure based on the perspective of the three energy sources (i.e., coal, oil and natural gas).To this end, we rewrite Eq. (2) as

$$C^t = \sum_j \frac{E_j^t}{E^t} \times E^t \times F_j \times \frac{44}{12} \tag{4}$$

where $E^t = \sum_i (E_i^t)/(Y_i^t) \times (Y_i^t)/(Y^t) \times Y^t$, indicating the total final energy consumption in year t, while E_j^t means the total final energy consumption of energy source j. Then the energy-related CO_2 emissions can be obtained from the following equation:

$$C^t = \sum_{i,j} CS_j^t \times EI_i^t \times IS_i^t \times Y^t \times F_j \times \frac{44}{12} \tag{5}$$

where $CS_j^t = (E_j^t)/(E^t)$, indicating the final energy consumption structure based on the three energy sources, which similarly appears in Wang et al. [30].

No matter which decomposition form above is adopted, the changes of CO_2 emission can be decomposed into those caused by economic growth, energy intensity, industrial structure and final energy consumption structure. Since the study period in this paper is not very long, we presume that the carbon coefficients of coal, oil and natural gas maintain steady across the whole period. Then

according to the LMDI approach proposed by Ang [18] and the decomposition forms in Eqs. (3) and (5), we decompose the CO_2 emission changes from C^0 in the base year to C^t in year t as follows:

$$\Delta C^t = \Delta C^t_{gdp} + \Delta C^t_{ei} + \Delta C^t_{is} + \Delta C^t_{cs} \tag{6}$$

$$\Delta C^t_{gdp} = \sum_{i,j} w\left(C^t_{ij}, C^0_{ij}\right)\ln\left(\frac{Y^t}{Y^0}\right) \tag{6a}$$

$$\Delta C^t_{ei} = \sum_{i,j} w\left(C^t_{ij}, C^0_{ij}\right)\ln\left(\frac{EI^t_i}{EI^0_i}\right) \tag{6b}$$

$$\Delta C^t_{is} = \sum_{i,j} w\left(C^t_{ij}, C^0_{ij}\right)\ln\left(\frac{IS^t_i}{IS^0_i}\right) \tag{6c}$$

$$\Delta C^t_{cs} = \sum_{i,j} w\left(C^t_{ij}, C^0_{ij}\right)\ln\left(\frac{CS^t_{i,j}}{CS^0_{i,j}}\right) \tag{6d}$$

$$w\left(C^t_{ij}, C^0_{ij}\right) = \frac{C^t_{ij} - C^0_{ij}}{\ln C^t_{ij} - \ln C^0_{ij}} \tag{6e}$$

where ΔC^t means the CO_2 emission changes from C^0 to C^t; ΔC^t_{gdp}, ΔC^t_{ei}, ΔC^t_{is} and ΔC^t_{cs} represent CO_2 emission changes caused by economic growth, energy intensity, industrial structure and final energy consumption structure respectively. It should be noted that the final energy consumption structure can be further decomposed from the perspectives of industrial structure and energy sources as mentioned below.

3.3. Carbon emission intensity change decomposition approach

Based on the definitions above, carbon emission intensity often means the CO_2 emissions per unit of GDP, which can be decomposed as follows:

$$I^t = \frac{C^t}{Y^t} = \sum_i \frac{E^t_i}{Y^t_i} \times \frac{Y^t_i}{Y^t} \times \frac{C^t_i}{E^t_i} \tag{7}$$

where I^t means the carbon emission intensity in year t; C^t_i represents the final energy-related CO_2 emissions of industry i; the denotations of other symbols are the same as above. And the last item in the right side $((C^t_i)/(E^t_i))$ can be rewritten as follows:

$$FS^t_i = \frac{C^t_i}{E^t_i} = \frac{\sum_j C^t_{ij}}{E^t_i} = \frac{\sum_j E^t_{ij} \times F_j \times \frac{44}{12}}{E^t_i} \tag{8}$$

Because of the assumption of stable carbon coefficient F_j, we define FS^t_i as the final energy consumption structure. Thus Eq. (7) can be expressed as follows:

$$I^t = \sum_i EI^t_i \times IS^t_i \times FS^t_i \tag{9}$$

According the LMDI approach, the change of carbon emission intensity from I^0 in the base year to I^t in year t can be decomposed as follows:

$$\Delta I^t = \Delta I^t_{ei} + \Delta I^t_{is} + \Delta I^t_{fs} \tag{10}$$

$$\Delta I^t_{ei} = \sum_i w\left(C^t_i/Y^t, C^0_i/Y^0\right)\ln\left(\frac{EI^t_i}{EI^0_i}\right) \tag{10a}$$

$$\Delta I^t_{is} = \sum_i w\left(C^t_i/Y^t, C^0_i/Y^0\right)\ln\left(\frac{IS^t_i}{IS^0_i}\right) \tag{10b}$$

$$\Delta I^t_{fs} = \sum_i w\left(C^t_i/Y^t, C^0_i/Y^0\right)\ln\left(\frac{FS^t_i}{FS^0_i}\right) \tag{10c}$$

$$w\left(C^t_i/Y^t, C^0_i/Y^0\right) = \frac{C^t_i/Y^t - C^0_i/Y^0}{\ln(C^t_i/Y^t) - \ln\left(C^0_i/Y^0\right)} \tag{10d}$$

where ΔI^t means the change of carbon emission intensity; ΔI^t_{ei}, ΔI^t_{es} and ΔI^t_{fs} indicate carbon emission intensity changes caused by energy intensity, industrial structure and final energy consumption structure respectively.

3.4. The decoupling measurement between CO_2 emissions and economic growth

Based on the decomposition results of final energy-related CO_2 emission changes, we combine the LMDI approach with the decoupling index as Diakoulaki and Mandaraka [39] adopted to analyze the decoupling relationship between CO_2 emissions and economic growth in China. During the research period (1996–2010), according to the previous literature, China's economy experienced rapid growth, which eventually contributed to the increase of CO_2 emissions. On the other hand, the decrease of energy intensity, the upgrading of industrial structure and the cleaning of energy consumption structure in the past decades may directly or indirectly reduce CO_2 emissions. Therefore, we use ΔF^t to represent the total inhibiting effect on CO_2 emissions as follows:

$$\Delta F^t = \Delta C^t - \Delta C^t_{gdp} = \Delta C^t_{ei} + \Delta C^t_{is} + \Delta C^t_{cs} \tag{11}$$

Then the decoupling index is defined as follows:

$$D^t = -\frac{\Delta F^t}{\Delta C^t_{gdp}} = D^t_{ei} + D^t_{is} + D^t_{cs} \tag{12}$$

where D^t means the total decoupling index, while D^t_{ei}, D^t_{is} and D^t_{cs} mean the influence of energy intensity, industrial structure and final energy consumption structure on the decoupling between CO_2 emissions and economic growth respectively. If $D^t \geq 1$, which denotes the *absolute decoupling effect*, we can say that the total carbon reduction effect of those inhibiting factors is greater than the driving effect of economic growth; putting it in another way, China's economy grows while its CO_2 emission declines. If $1 > D^t > 0$, which indicates the *relative decoupling effect*, we can say that the carbon reduction effect appears weaker than the driving effect; putting it in another way, China's economy grows with the increased CO_2 emissions. And if $D^t \leq 0$, which implies that there is no decoupling effect, we can say that the possible inhibiting factors do not play significant roles in decreasing CO_2 emissions and increasing CO_2 emissions instead. As for D^t_{ei}, D^t_{is} and D^t_{cs}, if their values are greater than 0, we can say that there exists inhibiting effect on CO_2 emissions caused by energy intensity, industrial structure and final energy consumption structure respectively, and they make contribution to the decoupling between CO_2 emissions and economic growth. Otherwise, there exists promoting effect on CO_2 emissions, and they have no contribution to the decoupling progress.

3.5. Data definitions

In this paper, the study period ranges from 1996 to 2010, covering the 9th, 10th and 11th Five-Year Plan periods in China. As for the economic data, we adopt the GDP and added value of the primary, secondary and tertiary industries, which are quoted in 100 million yuan in 1978 constant RMB price and come from China Statistical Yearbook 1997–2011 [43]. As for the energy data, we use the final consumption of coal, oil and natural gas in the three industries, which are quoted in ten thousand tons of coal

equivalent and come from China Energy Statistical Yearbook 1997–2011 [44].[1] Note that here the primary industry mainly includes the farming, forestry, animal husbandry and fishery conservancy; the secondary industry mainly consists of industry and construction; and the tertiary industry mainly covers transport, storage and post, wholesale, retail trade and hotel, restaurants and others. Besides, all the calculations are conducted in the Excel software.

4. Empirical results and analyses

4.1. Decomposition results of CO_2 emission changes

The decomposition results of final energy-related CO_2 emission changes are shown in Table 4, and several findings are identified as follows.

First, CO_2 emission almost kept increasing over the period 1996–2010 except some years such as 1997, 2000 and 2001. Specifically, carbon emissions have grown 1.218 billion tons with an annual growth rate of 4.3%. In particular, the growth rates reached 17% and 20.8% in 2003 and 2004 respectively, which were the highest rates during 1996–2010.

Second, economic growth appeared the main contributor to the increase of CO_2 emissions during 1996–2010, which is in line with the results of an array of previous literature [31,45]. According to the decomposition results, ΔC_{gdp}, which means the CO_2 emission changes from economic growth, was increased by 2.679 billion tons during the period of 1996–2010, which is 2.2 times of the total CO_2 emission changes. Over the past decades, China's economy has experienced sustained take-off and the average growth rate during 1996–2010 reached 9.6%. Even during the period of the international financial crisis in 2009, the growth rate still achieved 9.2%. However, it cannot be ignored that the enviable economic growth was supported by tremendous energy consumption. During 1996–2010, the total final energy consumption of China increased from 1.29 billion tons coal equivalent to 3.05 billion tons. Currently, China stands on its critical stage of industrialization and urbanization, which may continually consume more energy and emit more carbon dioxide, and the top priority has been given to ensure stable and sustained economic growth. Therefore, it is expected that economic growth remains a main contributor to the increase of carbon emissions in the long future.

Third, energy intensity proved the major inhibiting factor for CO_2 emissions as far as the factors are concerned in this paper, followed by final energy consumption structure. As the ratio of energy consumption and GDP, the decrease of energy intensity often indicates the improvement of energy use efficiency. During the period of 1996–2010, energy intensity in China has declined from 6.39 tce per ten thousand yuan to 4.06 tce per ten thousand yuan with an average annual decline rate of 2.97%. The decreased energy intensity caused 1.097 billion tons of carbon emissions reduction accumulatively (i.e., ΔC_{ei}), which accounted for 90.1% of total CO_2 emission changes. In particular, the reduction effect of energy intensity even exceeded the promoting effect of economic growth in 1997 and 1998, because of the shutting down of a group enterprises characterized by “high energy consumption, heavy pollution and low efficiency”. On the other hand, because of the cleaning of energy consumption structure during the period of 1996–2010, the CO_2 emission caused by energy consumption structure adjustment (i.e., ΔC_{cs}) was reduced by 555 million tons, which accounted for 45.6% of the total changes. And the inhibiting

[1] All the original data sets can be obtained in the Excel format from the authors upon request.

Table 4
The decomposition of final energy-related CO_2 emission changes.

Time period	ΔC_{tot}	ΔC_{gdp}	ΔC_{ei}	ΔC_{is}	ΔC_{cs}
1996–1997	−3953	13,213	−13,925	1383	−4619
1997–1998	1936	11,139	−11,498	1107	1188
1998–1999	3012	11,025	−6382	839	−2470
1999–2000	−1018	12,233	−8100	1199	−6350
2000–2001	−3060	11,890	−7582	501	−7869
2001–2002	6243	13,100	−5635	923	−2145
2002–2003	26,207	15,914	5721	2426	2147
2003–2004	37,429	19,035	10,201	1160	7034
2004–2005	7312	23,690	−2900	1132	−14,610
2005–2006	9606	27,396	−7393	1195	−11,593
2006–2007	8336	31,591	−14,440	1535	−10,350
2007–2008	13,134	22,924	−14,372	533	4051
2008–2009	11,449	23,052	−11,736	1130	−997
2009–2010	5120	26,799	−15,920	2337	−8106
1996–2010	121,754	267,903	−109,695	19,061	−55,521

Note: The time period ‘1996–1997’ in the table means that from the year 1996 to 1997, and other time periods have the similar meaning. ΔC_{tot} means the total CO_2 emission changes over time; ΔC_{gdp}, ΔC_{ei}, ΔC_{is} and ΔC_{cs} indicate the CO_2 emission changes caused by economic growth, energy intensity, industrial structure and final energy consumption structure respectively and all of them are quoted in ten thousand tons.

effect of final energy consumption structure was even greater than that of energy intensity in 2005 and 2006. As a matter of fact, the energy consumption structure in China proves cleaner gradually. During 1996–2010, the proportion of natural gas in the total energy consumption has increased from 1.8% to 4.4%, while the proportion of energy like hydro power and nuclear power has increased from 6.0% to 7.8%. These decomposition findings are consistent with the arguments of Asian/World Energy Outlook 2013 proposed by the Institute of Energy Economic of Japan (IEEJ) recently, which predicts that between the reference scenario and advanced technology scenario, the reduction of China's CO_2 emissions may be accounted for 47% by energy saving and 29% by fuel switching (and 24% by CCS) during 2011–2040.

Finally, there exists some promoting effect of industrial structure on CO_2 emission increase. During the period of 1996–2010, the CO_2 emission resulting from industrial structure adjustment (i.e., ΔC_{is}) was increased by 191 million tons accumulatively, which only accounted for 15% of the total CO_2 emission changes and was less than 8% of CO_2 emissions growth contributed by economic growth. It should be noted that the overall industrial structure did not change a lot during the study period. Specifically, although the ratio of the tertiary industry, which is featured by lower energy consumption and lighter carbon emissions, increased gradually in the national economy from 32.8% in 1996 to 43.1% in 2010, the secondary industry with higher energy consumption and carbon emissions still accounted for the major part, i.e., 46.8% in 2010. The enormous CO_2 emissions increment of the secondary industry offsets the carbon reduction effect coming from the adjustment of industrial structure. Therefore, in the “Work Plan of Controlling Greenhouse Gas Emissions during the 12th Five-Year Plan period”, Chinese central government proposes to speed up the adjustment of industrial structure and pay more attention to the development of service and strategic emerging industries with the targeted shares 47% and 8% in the national economy by 2015 respectively.

Moreover, we further explore the effect of energy intensity and industrial structure changes on CO_2 emissions. The results are shown in Table 5, from which several points are gained.

(1) The carbon reduction effect coming from the decreased energy intensity in the secondary industry accounts for about 80% of the total reduction effect contributed by energy intensity decrease, with 886 million tons of CO_2 emissions reduced

Table 5
The influence of energy intensity and industrial structure changes on CO_2 emissions.

Time period	ΔC_{ei}	ΔC_{ei1}	ΔC_{ei2}	ΔC_{ei3}	ΔC_{is}	ΔC_{is1}	ΔC_{is2}	ΔC_{is3}
1996–1997	−13925	−143	−10903	−2879	1383	−234	1231	386
1997–1998	−11498	−153	−9231	−2113	1107	−173	1133	147
1998–1999	−6382	−10	−5121	−1251	839	−190	554	474
1999–2000	−8100	46	−6671	−1475	1199	−238	1059	378
2000–2001	−7582	96	−5607	−2071	501	−222	147	576
2001–2002	−5635	101	−4347	−1390	923	−262	769	415
2002–2003	5721	562	3284	1875	2426	−363	2963	−175
2003–2004	10,201	488	7193	2520	1160	−217	1388	−11
2004–2005	−2900	92	−2311	−680	1132	−410	1145	397
2005–2006	−7393	−54	−5523	−1815	1195	−551	1071	675
2006–2007	−14,440	−406	−10,189	−3845	1535	−732	1369	897
2007–2008	−14,372	−635	−10,242	−3495	532	−287	403	416
2008–2009	−11,736	−16	−9582	−2139	1130	−344	1276	197
2009–2010	−15,920	−48	−15,414	−458	2337	−440	3188	−412
1996–2010	−109,695	172	−88,561	−21,305	19,061	−4600	18,580	5080

Note: The time period '1996–1997' in the table means that from the year 1996 to 1997, and other time periods have the similar meaning. ΔC_{ei} and ΔC_{is} indicate CO_2 emissions changes caused by energy intensity and industrial structure respectively; ΔC_{ei1}, ΔC_{ei2} and ΔC_{ei3} denote CO_2 emissions changes caused by energy intensity in the three industries, i.e., $C^t_{ei(i)} = \sum_{i,j} w\left(C^t_{ij}, C^0_{ij}\right) \ln\left((EI^t_i)/(EI^0_i)\right)$ $(i = 1, 2, 3)$; and ΔC_{is1}, ΔC_{is2} and ΔC_{is3} mean CO_2 emissions changes caused by the added value of the three industries, i.e., $\Delta C^t_{is(i)} = \sum_{i,j} w\left(C^t_{ij}, C^0_{ij}\right) \ln\left((IS^t_i)/(IS^0_i)\right)$ $(i = 1, 2, 3)$. The unit is ten thousand tons.

during the period of 1996–2010. Among the three major industries in national economy, the energy intensity of the secondary industry owns the highest total decrease and average annual decrease rates, which declines from 6.98 tce per ten thousand yuan to 3.9 tce per ten thousand yuan with a total decrease of 44.08% and an average annual decrease of 3.8%. The secondary industry mainly includes industrial and construction sectors, which often have higher energy consumption and heavier carbon emissions. The data from China Energy Statistical Yearbook showed that the secondary industry consumed about 71.4% of total final energy use and emitted 72.3% of total CO_2 emissions in 2010; therefore the improvement of energy use efficiency and carbon reduction technology in the secondary industry plays vital roles in curbing CO_2 emissions.

(2) The decreased energy intensity in the tertiary industry contributed about 20% of the total reduction effect of energy intensity and reduced 213 million tons of CO_2 emissions accumulatively during the period of 1996–2010. The energy intensity of the tertiary industry declined from 3.05 tce per ten thousand yuan to 1.91 tce per ten thousand yuan with a total decrease of 37.43% and an average annual decrease of 3.08%. As mentioned above, the energy intensity of the tertiary industry has significant decrease rates, but the proportion of the secondary industry in national economy always proves the largest. Compared to the secondary industry, the tertiary industry has less reduction potential because of its less energy usage and more consumption of cleaner energy like electricity and heat. Specifically, compared to the secondary industry's 2.18 billion tons of final energy consumption and 0.5 billion tons of coal consumption in 2010, the case for the tertiary industry was 0.46 and 0.03 respectively. On the other hand, the primary industry often has the least energy consumption among the three industries, so its energy intensity change may only slightly affect CO_2 emissions, with 1.72 million tons of CO_2 emissions increased during the study period. In fact, the energy intensity of the primary industry remains stable basically with 1.4 tce per ten thousand yuan.

(3) The promoting effect of industrial structure on CO_2 emissions changes mainly comes from the secondary industry, with the driving force accounting for more than 90% of the total effect of industrial structure. The secondary industry in China has always played the most important role in the development of economic growth and also is characterized by higher energy consumption and heavier CO_2 emissions. The tertiary industry has been increasing gradually in the national economy but contributes less to CO_2 emissions increase, which benefits from the consumption of cleaner energy and higher energy use efficiency. Moreover, the primary industry, whose added value accounted for 10.1% in the national economy in 2010, has pretty weak inhibiting effect with only 4.6 million tons of CO_2 emissions decreased.

In addition, we further analyze the influence of final energy consumption structure changes on CO_2 emissions. The results are shown in Table 6, and some findings are obtained as follows.

(1) In view of energy sources, the reduction effect of final energy consumption structure mainly comes from coal. Benefited from the improvement of coal use efficiency and coal clean technology, the CO_2 emissions caused by coal consumption (i.e., ΔC_{cse1}) was reduced by 618 million tons during 1996–2010. On the other hand, because of the increasing usage of oil and natural gas, 63 million tons of CO_2 emission was promoted. Comparatively, it can be found that the carbon reduction potential of coal is immense. As the principal energy source in China, coal is given the strategic role in the economic growth of the country. According to the official data from China's National Bureau of Statistics, the coal consumption accounted for about 68% of the total energy consumed in China in 2010. Because of China's rich resource endowment of coal and relatively cheaper coal price, coal will continue to be a key component of the primary energy mix in China in the long future [46]. But in order to reach the national carbon emissions reduction targets, China needs to set a quantitative cap for coal consumption as soon as possible and continue to improve the coal use efficiency and coal clean technology; meanwhile the consumption of clean energy like hydro power, wind power and solar power should be enhanced. In China's recent "Atmospheric Pollution Prevention Action Plan", the government proposes a goal to drop the rate of coal usage in the total energy consumption below 65% by 2017.

(2) In view of industrial structure, the reduction effect of final energy consumption structure mainly comes from the secondary industry. During the period of 1996–2010, the cleaning of final energy consumption structure in the secondary industry

Table 6
The influence of final energy consumption structure changes on CO_2 emissions.

Time period	ΔC_{cs}	ΔC_{cse1}	ΔC_{cse2}	ΔC_{cse3}	ΔC_{csi1}	ΔC_{csi2}	ΔC_{csi3}
1996–1997	−4619	−7588	3349	−380	−106	−3778	−735
1997–1998	1188	−375	1498	64	−45	1679	−447
1998–1999	−2470	−5088	2237	381	−201	−2125	−144
1999–2000	−6350	−8510	1951	210	−16	−6080	−253
2000–2001	−7869	−7582	−592	305	−155	−7179	−535
2001–2002	−2145	−3227	1008	74	181	−2549	223
2002–2003	2147	5827	−3860	181	183	2762	−798
2003–2004	7034	8092	−801	−258	467	6026	541
2004–2005	−14,610	−10,279	−4470	140	343	−14,225	−728
2005–2006	−11,593	−10,816	−1385	608	−134	−10,614	−845
2006–2007	−10,350	−10,227	−829	706	−379	−9702	−269
2007–2008	4051	4143	−1283	1191	−20	4887	−817
2008–2009	−997	2366	−3108	−255	51	13	−1060
2009–2010	−8106	−13,392	6630	−1344	98	−7306	−898
1996–2010	−55,521	−61,815	4025	2268	164	−49,556	−6129

Note: The time period '1996−1997' in the table means that from the year 1996 to 1997, and other time periods have the similar meaning. ΔC_{cs} means the CO_2 emissions changes caused by final energy consumption structure changes; ΔC_{cse1}, ΔC_{cse2} and ΔC_{cse3} indicate the CO_2 emissions changes caused by coal, oil and natural gas consumption respectively, i.e., $\Delta C^t_{cse(j)} = \sum_{i,j} w\left(C^t_{ij}, C^0_{ij}\right) \ln\left((CS^t_j)/(CS^0_j)\right)$ $(j = 1, 2, 3)$; and ΔC_{csi1}, ΔC_{csi2} and ΔC_{csi3} show the CO_2 emissions changes caused by the final energy consumption structure changes in the primary, secondary and tertiary industries respectively, i.e., $\Delta C^t_{csi(i)} = \sum_{i,j} w\left(C^t_{ij}, C^0_{ij}\right) \ln\left((CS^t_i)/(CS^0_i)\right)$ $(i = 1, 2, 3)$. The unit is ten thousand tons.

decreased 496 million tons of CO_2 emissions (i.e., ΔC_{csi2}), which accounted for 89.3% of the total CO_2 emissions reduced by the cleaning of final energy consumption structure (i.e., ΔC_{cs}). The reason is obvious. By the end of 2010, the added value of the secondary industry accounted for 46.8% in the national economy, as the dominant industry, and the secondary industry consumed about 71.4% of total final energy consumption. Therefore, the inhibiting effect on CO_2 emissions coming from the secondary industry played a very important role during the carbon reduction process. Moreover, during the research period, the cleaning of final energy consumption structure in the tertiary industry produced weak suppression effect on CO_2 emissions with 61 million tons of CO_2 emissions decreased accumulatively.

In brief, economic growth still proves the major contributor to CO_2 emissions increase while the decrease of energy intensity and the cleaning of final energy consumption structure play significant roles in the carbon reduction process, which are consistent with the results by Wang [26]. Moreover, in some individual years, the carbon reduction effect of final energy consumption structure is greater than that of energy intensity. In addition, the secondary industry is the key object to achieve China's carbon emission reduction goals and the government should strictly control the cap of coal consumption, continually drop the ratio of coal consumption in the total primary energy consumption and strenuously develop the mechanisms for clean coal production and efficient coal use.

4.2. Decomposition results of carbon emission intensity changes

The decomposition results of carbon emission intensity changes are shown in Table 7. Several findings are identified as follows.

(1) The carbon emission intensity in China dropped significantly during the research period and similar results appear in the study of Geng et al. [47]. Specifically, carbon emission intensity in China decreased from 0.748 kg/yuan in 1996 to 0.363 kg/yuan in 2010 with an annual decreasing rate of 5.03%. Especially in 1997 and 2001, the decrease rate even reached 10.91% and 9.54% respectively.

(2) The decrease of energy intensity is the primary inhibiting factor for carbon emission intensity and drops carbon emission intensity about 0.287 kg/yuan, which accounts for 74.43% of the total changes. Therefore, energy intensity can not only curb CO_2 emissions but also contribute to the decrease of carbon emission intensity, just as Zhang et al. [31] mentioned. At present, since coal is still the major energy consumption source in China, the improvements of coal use efficiency and coal clean technology are the key outlets to drop carbon emission intensity.

(3) The effect of cleaning final energy consumption structure is also remarkable to drop carbon emission intensity about 0.148 kg/yuan, which accounts for 38.5% of the total changes and denotes the second most significant inhibiting factor following energy intensity overall. More use of clean and renewable energy is the long-lasting trend for China's energy consumption structure adjustment. In 2010, non-fossil energy like hydro power and nuclear power accounted for 7.8% of total energy consumed in China. In order to further reduce CO_2 emissions and carbon emission intensity, the government put forward a target to increase the rate of non-fossil energy in primary energy consumption to 11.4% by the year of 2015 and 15% by 2020.

(4) Industrial structure always played a relatively weaker role in promoting carbon emission intensity, with an increase of 0.05 kg/yuan accumulatively during 1996–2010. Now the secondary industry bears relatively higher energy consumption and heavier CO_2 emissions, but it is still the dominant industry in China, which accounted for 46.8% in the national economy in 2010. Therefore, in order to sharply decrease carbon emission intensity, China has to put the upgrading of industrial structure at the first place and suppress or eliminate the excess capacities in the secondary industry, which is often characterized by higher energy consumption and serious pollution, and improves the energy use efficiency. On the other hand, China also needs to pay great attention to developing IT, financial and service sectors, which have lower energy consumption and less CO_2 emissions.

To sum up, in order to achieve the carbon emission intensity reduction targets, China needs to focus on the two most important inhibiting factors, i.e., energy intensity and final energy consumption structure, and aim at the breakthrough in the secondary

Table 7
The decomposition of carbon emission intensity changes.

Time period	ΔI_{tot}	ΔI_{ei}	ΔI_{fs}	ΔI_{is}
1996–1997	−0.816	−0.662	−0.220	0.066
1997–1998	−0.403	−0.503	0.052	0.048
1998–1999	−0.326	−0.259	−0.100	0.034
1999–2000	−0.498	−0.305	−0.239	0.045
2000–2001	−0.519	−0.263	−0.273	0.017
2001–2002	−0.219	−0.180	−0.068	0.029
2002–2003	0.299	0.167	0.062	0.071
2003–2004	0.486	0.270	0.186	0.031
2004–2005	−0.392	−0.069	−0.349	0.027
2005–2006	−0.380	−0.158	−0.248	0.026
2006–2007	−0.438	−0.272	−0.195	0.029
2007–2008	−0.165	−0.242	0.068	0.009
2008–2009	−0.178	−0.180	−0.015	0.017
2009–2010	−0.304	−0.223	−0.113	0.033
1996–2010	−3.852	−2.867	−1.483	0.498

Note: The time period '1996–1997' in the table means that from the year 1996 to 1997, and other time periods have the similar meaning. ΔI_{tot} means the total changes of carbon emission intensity; ΔI_{ei}, ΔI_{fs} and ΔI_{is} indicate the carbon emission intensity changes caused by energy intensity, final energy consumption structure and industrial structure respectively. The unit is kg/yuan.

Table 8
The decoupling between CO_2 emissions and economic growth.

Time period	D	D_{ei}	D_{is}	D_{cs}	Decoupling effect
1996–1997	1.299	1.054	−0.105	0.350	Absolute
1997–1998	0.826	1.032	−0.099	−0.107	Relative
1998–1999	0.727	0.579	−0.076	0.224	Relative
1999–2000	1.083	0.662	−0.098	0.519	Absolute
2000–2001	1.257	0.638	−0.042	0.662	Absolute
2001–2002	0.523	0.430	−0.070	0.164	Relative
2002–2003	−0.647	−0.359	−0.152	−0.135	No decoupling
2003–2004	−0.966	−0.536	−0.061	−0.370	No decoupling
2004–2005	0.691	0.122	−0.048	0.617	Relative
2005–2006	0.649	0.270	−0.044	0.423	Relative
2006–2007	0.736	0.457	−0.049	0.328	Relative
2007–2008	0.427	0.627	−0.023	−0.177	Relative
2008–2009	0.503	0.509	−0.049	0.043	Relative
2009–2010	0.809	0.594	−0.087	0.302	Relative
1996–2010	0.546	0.409	−0.071	0.207	Relative

Note: The time period '1996–1997' in the table means that from the year 1996 to 1997, and other time periods have the similar meaning. D means the total decoupling index (effect); D_{ei}, D_{is} and D_{cs} indicate the effect of energy intensity, industrial structure and final energy consumption structure changes on the decoupling progress respectively.

industry by improving energy use efficiency, upgrading industrial structure, reducing the consumption of fossil fuel especially coal and developing the clean and renewable energy.

4.3. Analyses of the decoupling between CO_2 emissions and economic growth

The total decoupling index between CO_2 emissions and economic growth and the influence of energy intensity, industrial structure and final energy consumption structure changes on the decoupling progress are shown in Table 8. And some insightful results are acquired.

First, the total decoupling index ranges during 0–1 in most years, which indicates the *relative decoupling effect* between CO_2 emissions and economic growth and the carbon reduction effect coming from inhibiting factors is less than the driving effect contributed by economic growth. It means that when the economy grows, CO_2 emissions increase too. However, it should be noted that the total decoupling indices were 1.299, 1.083 and 1.257 in 1997, 2000 and 2001 respectively, all greater than 1, which shows the *absolute decoupling effect*. In fact, in the three years, the economic growth accompanies with the reduction of CO_2 emissions. In other words, the reduction effect of inhibiting factors like energy intensity on CO_2 emissions appears more than the driving effect of economic growth. This mainly results from the Asian financial crisis in 1997 and the rare flood disaster in 1998, which hinder the energy consumption in China heavily. The growth rates of energy consumption were 0.40% and 0.51% respectively in 1997 and 1998, while the average growth rate was 6.47% during 1996–2010. Moreover, the government has shut down a group of enterprises characterized by "high energy consumption, heavy pollution, and low efficiency" simultaneously. Besides, the total decoupling indices were negative in 2003 and 2004 with −0.647 and −0.966 respectively, which means there is no decoupling effect between the rapid growth of economy and CO_2 emissions. Putting it in another way, those inhibiting factors including energy intensity, industrial structure and final energy consumption structure changes did not play significant roles in the carbon reduction process and turned into contributors to CO_2 emissions increase together with economic growth. Specifically, in 2003 and 2004, the growth rate of CO_2 emissions reached 17% and 20.8% respectively while the average during 1996–2010 was only 4.3%.

Second, the effect of energy intensity change on the decoupling progress (i.e., D_{ei}) is greater than zero in most years even greater than one in some years, which implies the promoting effect on the decoupling between CO_2 emissions and economic growth. And D_{ei}overall accounted for 75.1% of the total decoupling index (i.e., D) during 1996–2010. In particular, the contribution of energy intensity decrease to the decoupling process, which is mainly benefited from its apparent carbon reduction effect, appears more significant in those years with the absolute decoupling effect than that in other years. For example, in the absolute decoupling year 1997, the decrease of energy intensity reduced 1.39 billion tons of CO_2 emissions, even greater than that increased by economic growth, i.e., 1.32 billion tons, which is also the reason that D_{ei} is greater than one in 1997. Meanwhile, as the most important inhibiting factor to carbon emissions, energy intensity proves the biggest contributor to the decoupling relationship.

Third, the effect of industrial structure change on the decoupling progress (i.e., D_{is}) was always negative over the study period, which indicates that industrial structure does not make contribution to the decoupling between CO_2 emissions and economic growth. Similar to the decomposition results of CO_2 emissions changes above, the effect of industrial structure change on the decoupling proves relatively weaker, which only accounted for 13.04% of the total decoupling index on average during 1996–2010.

Fourth, the effect of final energy consumption structure change on the decoupling progress (i.e., D_{cs}) was almost over zero during 1996–2010 except for a few years, which means it is another contributor to the decoupling between CO_2 emissions and economic growth. Similar to energy intensity, the contribution mainly comes from the carbon reduction effect of cleaning energy consumption structure. In some particular years, the promoting effect of final energy consumption structure on the decoupling progress is even higher than that of energy intensity. For example, D_{ei} was 0.122 and 0.270 in 2005 and 2006 respectively while D_{cs} was 0.617 and 0.423 respectively.

Finally, there appears the *relative decoupling effect* between CO_2 emissions and economic growth in China in most years during 1996–2010, accounting for two-thirds (10/15) as shown in the last column in Table 8. The *absolute decoupling effect* only exists in three periods. And there is *no decoupling effect* in two periods, i.e., the year of 2003 and 2004. Moreover, the large share of the *relative decoupling effect* overall reflects the fact that although the decrease of energy intensity and the cleaning of final energy consumption structure play important roles in promoting the decoupling

progress through their significant carbon reduction effect, it still appears weaker than the promoting effect of economic growth. Therefore, in order to break the connection between CO_2 emissions and economic growth and achieve China's carbon emission intensity target, the government should still take effective measures to further decrease energy intensity and cleanse energy consumption especially coal consumption.

4.4. Policy recommendations

Based on the empirical analyses above, in order to achieve the target to reduce 40–50% of carbon emission intensity by 2020 compared to the level in 2005 and 17% by 2015 compared to the level in 2010, we put forward some policy recommendations for China's government as follows.

(1) The government is expected to continually transform economic growth pattern and upgrade industrial structure by innovative technologies. In particular, some effective policies (such as tax, subsidy) should be adopted to decrease the proportion of the industries with higher energy consumption and heavier carbon emissions and strive to deploy those low-carbon industries instead. On the one hand, the government can promote the marketing process of energy like coal, oil, natural gas and electricity. On the other hand, the government can impose energy tax and environmental tax to some specific industries depending on their energy consumption and CO_2 emissions conditions. The government can also create appropriate energy-saving and carbon reduction subsidies to accelerate the development of those low-carbon industries like the modern service industries.

(2) The government is advised to persistently improve the efficiency of energy consumption and vigorously expand the reduction potential of the secondary industry through eliminating backward production capacities and advancing the use efficiency and clean technology. It should also be noted that, in the wake of industry transformation especially in the urbanization process, the sectors in the tertiary industry with lower energy consumption and less carbon emissions should be enhanced further, such as the IT, financial sectors. The government can improve the efficiency of energy consumption through the cooperation between local enterprises and foreign advanced technologies, combining with some mandatory energy-saving and carbon reduction policies. As mentioned above, the development of the tertiary industry especially the modern service industry can be supported by macro-control means like tax and subsidy.

(3) The government ought to adjust the energy use structure in the secondary industry by dropping coal consumption, improving coal use efficiency and increasing the utilization of clean coal technologies. The government should encourage or help the secondary industry to adjust the energy use structure through drafting rewarding policies. Specific measures like dropping coal consumption and increasing the use of clean energy like natural gas and electricity. Improving coal use efficiency and increasing the utilization of clean coal technologies should be backed by the cooperation mentioned above. Besides, the market competition can also force the enterprises in the secondary industry to make those changes.

In conclusion, in order to achieve the promised carbon emissions intensity target, China needs to make full use of the two major inhibiting factors, i.e., energy intensity and final energy consumption structure, and strive for breakthrough in the secondary industry and coal consumption. Overall, China now is on the way of urbanization, industrialization and agricultural modernization, and its economic policies should be more closely combined with the energy development policies, environmental protection policies and climate change policies.

5. Conclusions and future work

In this paper, we decompose the changes of final energy-related CO_2 emissions and carbon emission intensity in China during the period of 1996–2010 to figure out the main affecting factors by using the LMDI approach. Meanwhile, we introduce the decoupling index to analyze the decoupling relationship between CO_2 emissions and economic growth. Several conclusions are obtained as follows.

(1) Economic growth proves the main contributor to increased CO_2 emissions during 1996–2010. Over the study period, China's CO_2 emissions caused by economic growth were increased by 2.679 billion tons, which is 2.2 times of the total CO_2 emission changes.

(2) Energy intensity and final energy consumption structure play significant roles in decreasing CO_2 emissions and carbon emission intensity, with a reduction of 1.652 billion tons of CO_2 emissions and 4.35 kg/yuan carbon emissions intensity. Moreover, the secondary industry proves the primary source of the reduction effect and still contains enormous reduction potential. When considering the energy use structure, the reduction effect of the decrease of coal consumption, the improvement of coal use efficiency and coal clean technology also cannot be ignored.

(3) In two-thirds of the study period, there appears the relative decoupling effect between final energy-related CO_2 emissions and economic growth in China. There was absolute decoupling effect in 1997, 2000 and 2001, whereas no decoupling effect was identified during 2003–2004. Moreover, the decrease of energy intensity and the cleaning of final energy consumption structure are the main facilitators to the decoupling between CO_2 emissions and economic growth in China.

This paper uses the LMDI approach to decompose China's CO_2 emissions and carbon emission intensity; however, the approach cannot reveal the effect from the changes of production technology and efficiency. Therefore, we may bring the PDA approach into use to incorporate the role of production technology and efficiency in the future, not only for the decomposition of CO_2 emissions but also for the decoupling between carbon emissions and economic growth.

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